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Dr. Siavouche Nemat-Nasser

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14. ABSTRACT
We have established the feasibility of creating mechanical metamaterials over a broad range of frequencies. We have shown that it is possible to have stress waves with negative dynamic effective modulus of elasticity or negative dynamic effective density within various windows of frequencies. We have indicated how one may design the microstructure of composites at several length scales in order to control stress waves over a range of wave-lengths, which has novel industrial and other applications. By controlling the spatial variation of anisotropy of the medium, stress waves can be made to follow desired trajectories, scattering can be controlled, and energy can be focused or dissipated.

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I. Personnel Supported:

Dr. Alireza Amirkhizi (Assistant Research Scientist) worked on theoretical understanding of negative refraction of stress waves in solids, experimental observation of this phenomenon, and design of samples with metamaterial response.

Dr. Ankit Srivastava (Postdoctoral Researcher) worked on homogenization of 2D and 3D composites in order to calculate their overall dynamic mechanical properties, followed by designing samples to verify these calculations.

Mr. Jon Isaacs (Engineer) worked on the design and fabrication of the 2D and 3D samples as well as the instrumentation and ultrasonic measurement of the wave propagation characteristics of the samples.

II. Comprehensive Summary of Significant Work Accomplished:

Mechanical metamaterials are defined as materials with overall properties that are not normally observed in nature, such as negative effective modulus of elasticity or effective density within a desired frequency interval. We have shown through numerical and experimental work the possibilities and potentials of designing such materials. Our focus has been on polymers, block copolymers and fiber-reinforced composites. The possibility of changing the morphology of such materials over broad ranges of length scales that subsequently can tune their overall response to stress waves or other stimuli provides novel opportunities with broad industrial and other applications.

By carefully designing the microstructure, stress waves can be managed at a wide range of length scales and frequencies to achieve,

- Nano to micro-structurally designed materials with controlled and tunable response

- Stress-wave redirection and focusing
- Negative effective mass and band gaps over windows of frequencies, which change or can be changed by an external stimuli.

It is possible for the length scale (*l*) of the microstructure to be a tenth of the macroscale wavelength and yet be able to affect the macroscale wave through resonance. In Figure 1 we have shown how this fact may be used to affect various length scales of dynamic response through hierarchical design of microstructure.

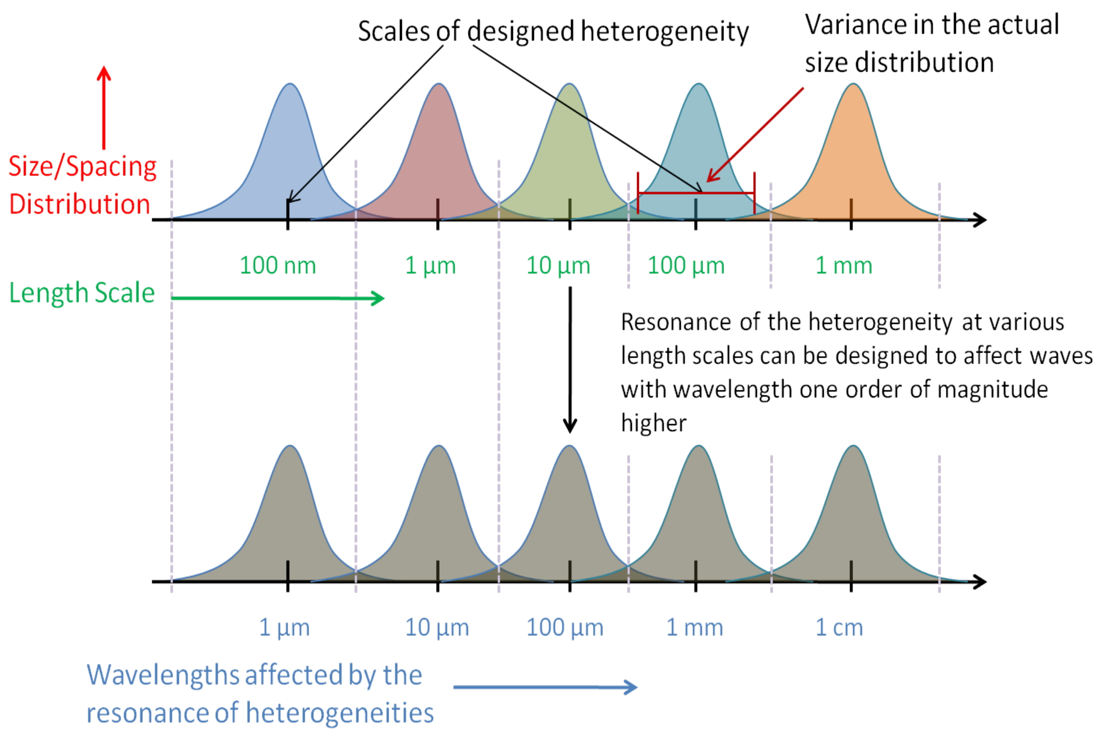

Fig. 1: Effect of resonance of the microstructure on the macroscale wavelengths.

Stress-wave redirection

By carefully controlling the spatial variation of anisotropy of the medium, stress waves can be made to follow desired trajectories, scattering can be controlled, and energy can be focused.

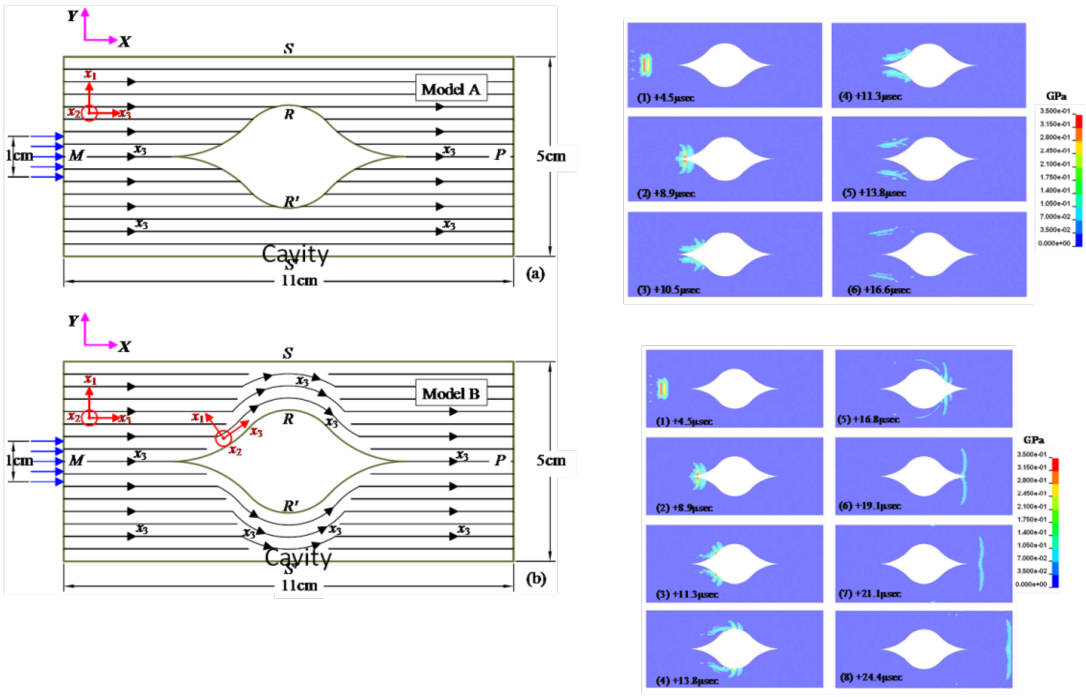

Fig. 2: Wave redirection through microstructural design of anisotropy

Figure 2, showing the numerical results published by Amirkhizi et. al., 2010 [*Wave Motion*, Vol. 47], demonstrates that such wave redirection is possible. In the top example (Model A) we have a homogeneous medium with a cavity. Stress wave directed at the cavity suffers scattering and is unable to reach the transmission side. Model B is specially designed to have spatially varying anisotropy and results in reduced scattering of the stress wave by the cavity. Numerical predictions above have been experimentally verified at CEAM and the results are published alongside the simulation results.

Wave redirection for controlled scattering has potential for improved protection and detection avoidance of sensitive objects, while focusing may increase the energy harvesting efficiency by creating high intensity nodes.

Negative effective mass and stiffness through microstructural design

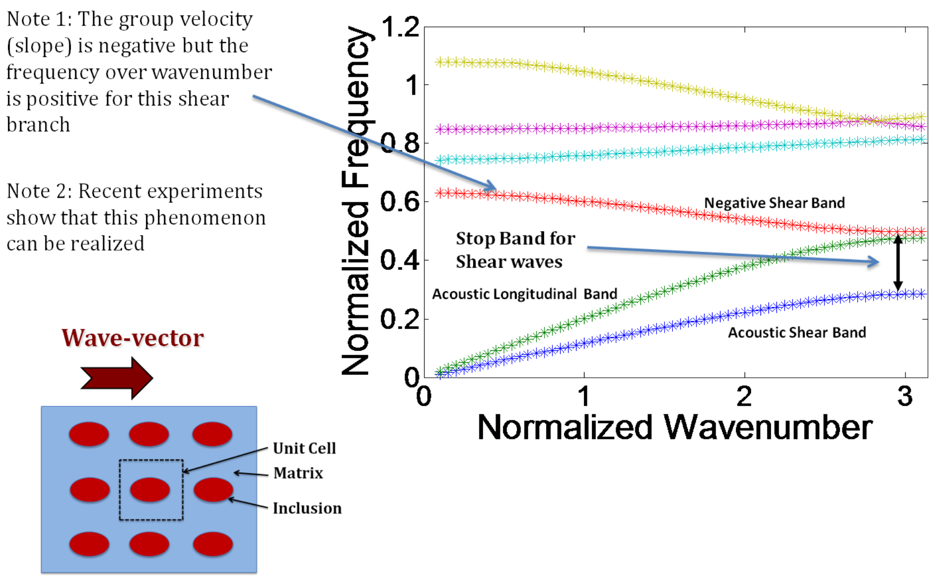

Fig. 3: Hard inclusions embedded in soft matrix: wave frequency vs. wavenumber

By carefully controlling the microstructure mechanical metamaterials can be designed to demonstrate bandgaps at desired frequencies and frequency windows. Furthermore, where the effective mass and stiffness are negative, one observes negative refraction, i.e. anti-parallel phase and group velocity. This effect is elaborated in Figure 3 for a negative shear band. Our 1D and 2D numerical designs clearly show these effects and we have also experimentally established the reliability of our numerical predictions by observing the band structures in ultrasonic testing.

Tunability

The band structure of layered and 2D or 3D periodic composites may be adjusted by changing one or two architectural parameters. For example in Figure 4 we change the internal spacing of two layers which results in significant reduction in the width of the stop band. In certain materials, such as elastomers, such dimensional changes may be achieved by applying relatively low pressure, therefore allowing for in-situ tuning of properties. In polyurea for example, small hydrostatic pressure also changes the shear modulus, which also contributes to the overall properties of the layered or 2D periodic media.

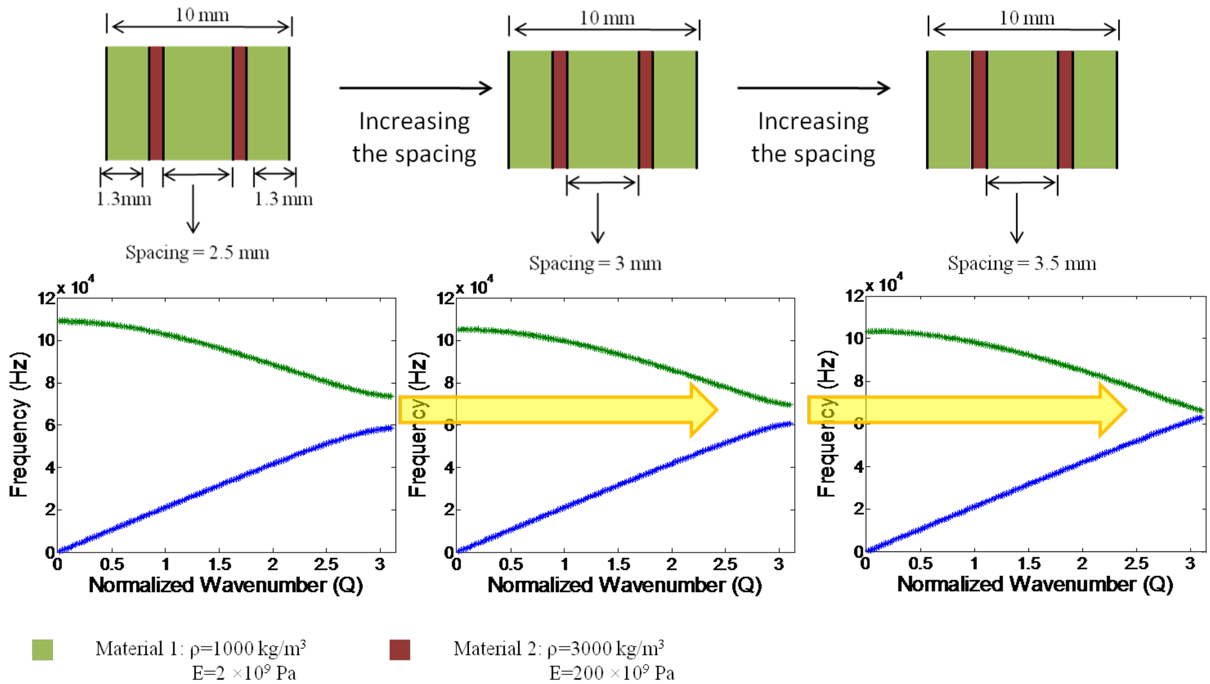

Fig. 4: Effect of changing the location of the micro-inclusion on the dispersion curve of the composite

III. Archival Publications

Amirkhizi, A.V., A. Tehranian and S. Nemat-Nasser, "Stress-wave Energy Management through Material Anisotropy," *Wave Motion,* Vol. 47 (2010) 519-536. Also acknowledges ONR Grant N00014-09-1-0547 to UC San Diego.

Abstract: Stress-wave propagation in solids can be controlled through imposing a gradual change of anisotropy in the material elasticity tensor. In this study, a transversely isotropic material is incorporated with a smoothly varying axis of anisotropy. It is shown that if this axis initially coincides with the stress-wave vector, then the energy of the plane waves would closely follow this gradually changing material direction. A fiber-reinforced composite is used to induce the required anisotropy, and to experimentally demonstrate the management of stress-wave energy in a desired trajectory. The material has isotropic mass-density and is considered homogeneous at the scale of the considered wavelengths, even though microscopically it is highly heterogeneous.

Nemat-Nasser, S., J.R. Willis, A. Srivastava and A.V. Amirkhizi, "Homogenization of periodic elastic composites and locally resonant sonic materials," *Phys. Review. B*, Vol. 83 (2011) 104103.

Abstract: A method for homogenization of an elastic composite with periodic microstructure is presented, focusing on the Floquet-type elastic waves. The resulting homogenized frequency-dependent elasticity and mass density then automatically satisfy the overall conservation laws and by necessity produce the exact dispersion relations. It is also shown that the dispersion relations and the associated

field quantities can be accurately calculated using a mixed variational approach, based on the microstructure of the associated unit cell. The method is used to calculate the dynamic effective parameters for a layered composite by using both the exact solution and the results of the mixed variational formulation. The exact and approximate results are shown to be in close agreement, which makes it possible to use the approximate method for the proposed type of homogenization in cases where an exact solution does not exist. The homogenized frequency-dependent effective parameters give rise to the concept of dynamic Ashby charts that can be used to illustrate the effect of the microstructural architecture on the dynamic properties of a composite. In particular, the charts vividly display how this effective stiffness and density vary with frequency and may attain negative values within certain frequency ranges which can be changed as desired using the microarchitecture while keeping the volume fraction of the unit cell's constituents constant.

Nemat-Nasser, S., and A. Srivastava, "Overall Dynamic Constitutive Relations of Micro-structured Elastic Composites" *J. of the Mech. and Phys. of Solids*, submitted 11/2010.

Abstract: A method for homogenization of a heterogeneous (finite or periodic) elastic composite is presented. It allows direct, consistent, and accurate evaluation of the averaged overall frequency-dependent dynamic material constitutive relations. It is shown that when the spatial variation of the field variables is restricted by a Bloch-form (Floquet-form) periodicity, then these relations together with the overall conservation and kinematical equations accurately yield the displacement or stress modeshapes and, necessarily, the dispersion relations. It also gives as a matter of course point-wise solution of the elasto-dynamic field equations, to any desired degree of accuracy. The resulting overall dynamic constitutive relations however, are general and need not be restricted by the Bloch-form periodicity. The formulation is based on micro-mechanical modeling of a representative unit cell of the composite proposed by Nemat-Nasser and coworkers; see, e.g., [1] and [2]. We show that, for a micro-structured elastic composite, the overall effective mass-density and compliance (stiffness) are always real-valued and positive, whether or not the corresponding unit cell (representative volume element used as a unit cell) is geometrically and/or materially symmetric. The average strain and linear momentum are however couple and the coupling constitutive parameters are always each others complex conjugates for any heterogeneous elastic unit cell, such that the overall energy-density is always real and positive. In this paper, we have sought to separate the overall constitutive relations which should depend only on the composition and structure of the unit cell, from the overall field equations which should hold for any elastic composite; i.e., we use only the local field equations and material properties to deduce the overall constitutive relations. It is shown, by way of an example of a bi-layered composite, that dispersion curves obtained by our method accurately produce the exact results of Rytov [3]. The method is also used to calculate the effective parameters for a 2-layered composite and the results are compared with those of homogenization based on the field integration of the exact solution (Willis [4], and Nemat-Nasser et al. [5]), and certain relevant issues are clarified. Finally the method is used to homogenize both a symmetric and a non-symmetric 4-layered composite and the results for the symmetric case are compared with those reported by Nemat-Nasser et al. [5] as well as the exact solution. Thus, this method provides a powerful solution and homogenization tool to use in many cases where the unit cell contains inclusions of complex geometry.

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[4] J.R. Willis, Exact effective relations for dynamics of a laminated body, *Mechanics of Materials*, **41** (2009), pp. 385-393.
[5] S. Nemat-Nasser, J. R. Willis, A. Srivastava, A. V. Amirkhizi, Homogenization of periodic elastic composites and locally resonant sonic materials, *Phys. Rev. B.*, Vol. 83 (2011) 104103.